40 YEARS OF ROCK ANCHORS FOR DAMS IN NORTH AMERICA – LESSONS LEARNED

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ABSTRACT

Over the last few years, the authors have acted as Co-Principal Investigators on a National Research Program on Rock Anchors for Dams. Three main tasks have been accomplished, leading to the development of a comprehensive database:

(i) comparative analysis of the five successive sets of "recommendations" governing practice (1974-2004);
(ii) compilation of over 230 technical papers describing North American case histories; and
(iii) development of details of over 400 projects executed on North American dams.

As a result, the authors are able now to provide a historical perspective to the art and science as it has evolved over the years. Technical guidance is provided on the key areas of design, corrosion protection, and construction practices. Cost information is also supplied as a first stage in project cost estimation.

EVOLUTION OF AMERICAN PRACTICE

Permanent post-tensioned rock anchors have been used in North America for more than 40 years. Although there are early documented cases of dam anchoring in North Africa in the 1930's, the first North American projects did not occur until the mid 1960's when the practice was adopted by the U.S. Army Corps of Engineers (USACE) and Montana Power Company. Two notable early projects include John Hollis Bankhead Lock & Dam in 1965 and Little Goose Locks & Dam in 1968.

The evolution of the "Recommendation" documents has had a very strong influence on North American anchoring practice. Recognizing the need for some type of national guidance and uniformity, tentative recommendations of practice for pre-stressed rock and soil anchors were first issued by the Post-Tensioning Division of the Prestressed Concrete Institute (PCI) in 1974. The Post-Tensioning Division of PCI formed an independent organization known as the Post-Tensioning Institute in 1976. In 1980, the Post-Tensioning Institute issued the First Edition of *Recommendations for Prestressed Rock and Soil Anchors* (PTI Recommendations) that were subsequently adopted and reprinted by the USACE. Successive editions of the PTI Recommendations were issued in 1986,

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1996, and 2004. A review of the successive recommendation documents reveals a clear evolution from promotional literature documenting case studies of projects to detailed guidance and commentary information on the primary areas of anchoring practice: Materials, Design, Corrosion Protection, Construction, and Stressing/Testing. More detailed analysis of the evolution of the PTI Recommendations may be found in Bruce and Wolfhope (2007a).

The early projects were performed by post-tensioning specialists from the building and transportation industries teamed up with drilling contractors to perform the required drilling and grouting. Although the fundamental design practices for the sizing of the bond zone and load transfer have not changed substantially over 40 years of practice, review of the early projects reveals that corrosion protection practices were inadequate until the 1990's. The early projects relied solely on grout cover around the prestressing steel to provide corrosion protection; it is now recognized that the grout in the bond zone crushes locally during stressing and testing and can provide seepage contact with the steel. Analysis of an isolated early project reveals evidence of tendon failure at the top of the bond zone after as little as 10 years of service in foundation conditions prone to water movement, providing confirmation of corrosion protection breakdown in the region of the highest grout to rock bond stresses. Although the use of plastic corrugated sheathing and epoxy coating is mentioned as available options in the 1980 PTI Recommendations, the use of an impermeable encapsulation was not prescribed until the 1986 PTI Recommendations.

Overall, between 1974 and 2006 extremely sophisticated corrosion protection systems were developed and the latitude offered to designers relative to the choice of corrosion protection intensity and details was severely restricted. The most recent 2004 edition provides a detailed coverage of corrosion protection practices including the use of corrugated plastic encapsulation over the full length of the anchor tendon and a separate supplement dealing with the specifications, materials, design, construction, and testing for the use of epoxy coated and filled strand. To install a permanent anchor in a dam without Class I (encapsulated tendon) protection is now not only impermissible, but unthinkable. Table 5.1 below, taken from the 2004 edition of the PTI Recommendations, provides the requirements for Class I corrosion protection.

Table 1 Corrosion Protection Requirements (taken from PTI Recommendations 2004)

CLASS	CORROSION PROTECTION REQUIREMENTS		
	ANCHORAGE	FREE STRESSING LENGTH	TENDON BOND LENGTH
1 ENCAPSULATED TENDON	Trumpet Cover if exposed	• Corrosion inhibiting compound-filled sheath encased in grout , or • Grout-filled sheath, or • Grout-encased epoxy-coated strand in a successfully water-pressure tested drill hole	• Grout-filled encapsulation, or • Epoxy-coated strand tendon in a successfully water-pressure tested drill hole
II GROUT PROTECTED TENDON	Trumpet Cover if exposed	• Corrosion inhibiting compound-filled sheath encased in grout, or • Grout-encased epoxy-coated bar tendon, or • Polyester resin for fully bonded bar tendons in sound rock with non-aggressive ground water	• Grout • Polyester resin in sound rock with non-aggressive ground water

It is now considered standard practice that modern prestressed rock anchor systems for dam construction and rehabilitation will provide service lives exceeding 50 years. Figure 1 and Figure 2 demonstrate the evolution of corrosion protection from bare steel tendons in grout to modern multi-level corrosion protection systems.

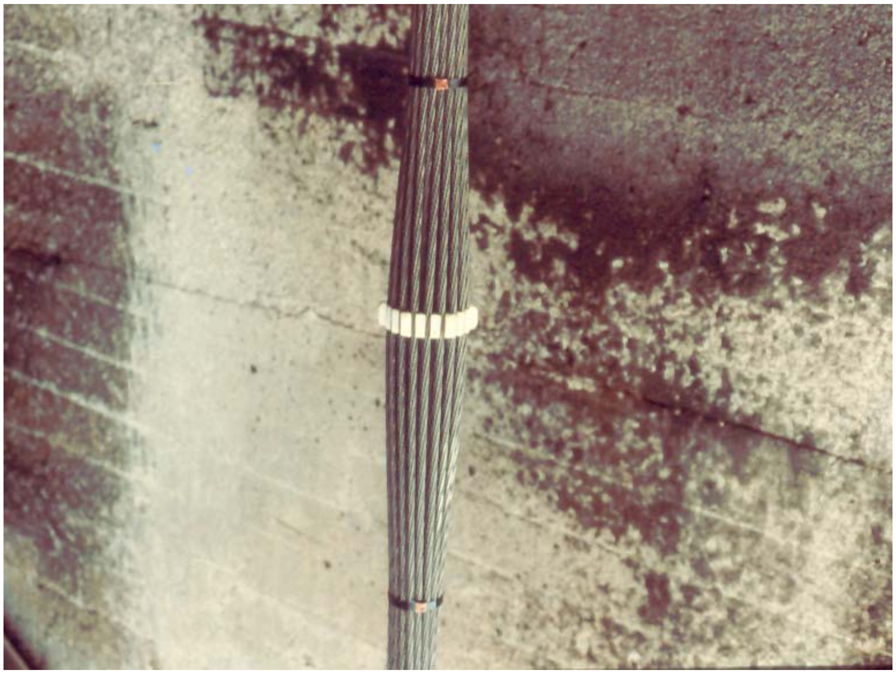

Figure 1. Bare Steel Multi-Strand Tendon

Figure 2. Fully Encapsulated Multi-Strand Tendon

Fortunately, the drilling and grouting practices for the early dam anchoring projects were (and remain) conservative with careful attention given to the grouting of the drilled anchor holes prior to tendon installation. The philosophy of pregrouting and redrilling the hole ("waterproofing") if it were to fail a permeability test was reaffirmed from 1974 onwards: indeed the early "pass-fail" acceptance criteria were, in fact, very rigorous and led to most anchors on most projects having to be pregrouted and redrilled several times. Although laudable, this was often, in fact, "extra work" since the criterion to achieve grout tightness is really much more lax than the criterion needed to provide the specified degree of water tightness. The saving grace of many of the early anchors was doubtless the overly conservative drill hole "waterproofing" criterion under which they were constructed.

OBSERVATIONS FROM DAM ANCHORING CASE STUDIES

As part of the National Research Program (Bruce and Wolfhope 2006) case studies have been developed for the more than 400 dam anchoring projects occurring throughout North America over the past 40 years. More than five anchoring dam projects have been successfully completed in each of over 25 U.S. states and three Canadian provinces, with only 10 states where prestressed tendon anchors have not been used in dam applications. The case studies have been compiled into a database repository for easy retrieval of information and analysis of statistical information. Although limited information exists on many of the older projects, the case studies for many of the projects from the last decade of practice include details on the anchor systems, corrosion protection, and the engineering aspects of the anchor design. The danger of losing remaining historical information, the original driver for the National Research Program, remains a threat to the full understanding of the evolution of American anchoring practice and the opportunity to improve practice based on lessons learned over 40 years of practice. It is apparent that the industry has historically been driven by regulatory changes that have resulted in the need for dams to accommodate increased hydrostatic and dynamic loading conditions while maintaining minimum acceptable stability safety factors. The use of prestressed anchors is often the only practically available option for increasing the sliding and overturning stability of overflow spillways and is typically two to three times less costly than mass concrete stabilization alternatives for non-overflow concrete gravity dams.

The use of prestressed anchors in dams has been well documented in over 230 published journal articles. It can be stated that no documented cases have been reported where a dam that has been anchored has failed. In general the case histories indicate good performance of the anchor systems. There are isolated situations where dams have been anchored multiple times due to poor performance of the anchors; these cases are undoubtedly attributable to inappropriate design approaches and construction techniques. Although there are questions as to the long term reliability of the early anchor tendons installed with grout cover as the sole corrosion barrier, the case studies of projects occurring over the past decade reveal the application of systematic design approaches including attention to the corrosion protection and the quality control aspects throughout construction and testing.

LESSONS LEARNED OVER 40 YEARS OF PRACTICE

Beyond the overall evolution of North American practice since the 1960's, significant advances have been made in specific aspects of the use and application of prestressed anchors for dams. The following sections identify lessons learned from the review of North American anchoring practice regarding design, corrosion protection, and construction practices – these being three key areas of anchor technology.

Design Aspects

- The conservative assumption of uniform bond stress distribution at the rock-grout interface remains the standard of practice. The recommended maximum bond stress values for various foundation conditions have remained essentially unchanged in the PTI recommendation documents over 30 years. This is a conservative state of affairs.
- The early use of multi-wire tendons has been replaced with the use of multiple seven-wire low-relaxation steel strand tendons since the 1980's. Multi-strand tendons have been installed in a variety of configurations ranging from low capacity tendons with 2 strands per tendon with a design load of less than 70 kips to high capacity tendons exceeding 90 strands per tendon with lock-off loads approaching 4000 kips. Multi-strand tendon lengths on dam anchoring projects range from as little as 30 feet to over 350 feet.
- The permissible capacity of the tendon is dictated by the integrity of the dam structure, the strength and uniformity of the foundation, and the configuration of

the structural elements of the dam. Even relatively weak dams such as poorly cemented cyclopean masonry structures and irregularly fractured unreinforced mass concrete structures have been successfully anchored using appropriate mechanisms for transfer and distribution of the post-tensioning forces into the structure.

- Bar tendons are used primarily for applications requiring relatively small post-tensioning forces (< 300 kips per tendon) and are practically limited to tendon lengths less than 60 feet. Bar tendons greater than 60 feet in length require the use of couplers that result in the need to oversize the anchor hole. As such, for tendons lengths greater than 60 feet, multi-stand tendons are typically more cost-effective per unit spacing.
- Test anchor programs during the design phase have been traditionally conducted and remain a good practice for tailoring the anchor system to site specific conditions. Test anchor programs are a valuable tool for establishing design bond strength parameters and for evaluating constructability aspects. Anchor programs should typically consist of two or more tendons to allow for anomalies in the test results and variations in the site geology.

Corrosion Protection

- It is imperative that rock anchors for dams be provided with Class I Corrosion Protection in accordance with the 2004 edition of the PTI Recommendations. Consistent with European practice, grout is not considered sufficient to prevent long term corrosion of the tendon elements. Proper corrosion protection requires the use of impervious barriers encapsulating the tendons over the entire length of the anchor hole and proper protection of the anchorage.
- When plastic corrugated sheathing is used to provide encapsulation of the tendon, multistage grouting of the outer annulus between the corrugated sheathing and the borehole wall is required to avoid crushing and distortion of the sheathing.
- Methods are available for systematically testing and demonstrating the effectiveness of the corrosion protection mechanisms at each stage of the construction process. An effective four step process for assuring the waterproofing of the borehole consists of: 1) water testing and pre-grouting (if necessary) the drilled hole, 2) water testing the corrugated sheathing prior to insertion, 3) water testing the corrugated sheathing following installation into the borehole, and 4) water testing of the sheathing following grouting of the annulus and prior to insertion of the tendon.
- The use of epoxy-coated and filled strand requires special care in the handling and stressing of anchor tendons, including a thorough understanding of the relaxation properties of the coated strand (Bruce 2002).
- The treatment of foundation conditions prone to water movement is an important consideration for ensuring adequate corrosion protection and to provide for effective grouting of the tendon bond zone. Pre-grouting using cement-fine aggregate mixtures is an effective tool for reducing the permeability and increasing the strength of weak foundation and dam conditions.

- To avoid compromising corrosion protection, the use of sentinel anchors (anchors installed for the purpose of "watching" the performance of the production anchors) is often preferred to the use of load cells on permanent production anchors where instrumentation is required by regulatory agencies to demonstrate the load term load holding performance of the tendon. Sentinel anchors are designed and installed using the same methods as production anchors and are often installed at an easily accessible off dam location that provides for easy long term monitoring using load cells. Bond zones for sentinel anchors are founded in similar lithologies to the production anchors.

Construction Practices

- The use of qualified contractors is critical to the successful drilling, installation, stressing, and testing of prestressed anchor systems for dams. Although the current state of practice provides for excellent and predictable results, dam owners are cautioned against attempts at trying to put together projects at the lowest possible cost by renting equipment and self performing the installation. Strict qualification requirements should be specified in bid documents to provide for the procurement of capable dam anchor specialists.
- Preproduction test anchors are a useful tool for demonstrating and refining the contractor's construction methods, testing apparatus, and quality control practices. Successful preproduction anchors that meet acceptance criteria are often incorporated into the completed project.
- Drill hole aligned tolerances of 1 in 100 are achievable with a standard level of care. Tolerances tighter than 1 in 100 are achievable with extra measures including the use of directionally drilled pilot holes.
- Down-hole hammer (percussion) drilling can typically be used in sensitive foundation conditions without causing adverse affects on the foundation or the structure, except in exceptional cases.
- Advances in drilling equipment technology allow for the drilling of holes in difficult locations.
- Industry has gained much knowledge about grout stability and rheology. Emphasis on fluid testing has become an effective indicator of grout quality, reducing the emphasis on laboratory testing of cured samples.
- Stressing and testing is typically conducted to a higher level of standard than was historically considered. On some jobs every anchor is subjected to cyclic Performance Testing (as opposed to simple Proof Testing) with little impact to the project cost or schedule.
- Long term load holding performance can be reliably predicted based on the properties of the prestressing steel provided that proper quality control and testing practices are followed. Qualified full-time resident engineering inspection is required to ensure adherence to proper construction practices.
- Documentation of performance data for anchor projects is limited and scattered throughout the pages of published journal articles over the past 30 years. Future phases of the National Research Program will be focused on documenting the performance aspects of prestressed rocks anchor systems in dams.

CONSTRUCTION COSTS

In compiling the anchor case study database of over 400 dam anchoring projects, meaningful construction cost information has to date been obtained for over 100 projects. The database captures the overall project construction cost and the more specific value of the anchoring aspects of the project. Graphs and statistics have been developed to identify a general relationship between the cost of the anchoring construction versus the overall length of drilled hole, and versus the overall length of pre-stressing steel installed in the project. All cost data were adjusted to a common baseline of 2007 construction costs using cost indices published by the U.S. Bureau of Reclamation (USBR) for concrete dam construction. Figure 3 provides a comparison of overall project drilling length to the adjusted cost of the anchoring construction.

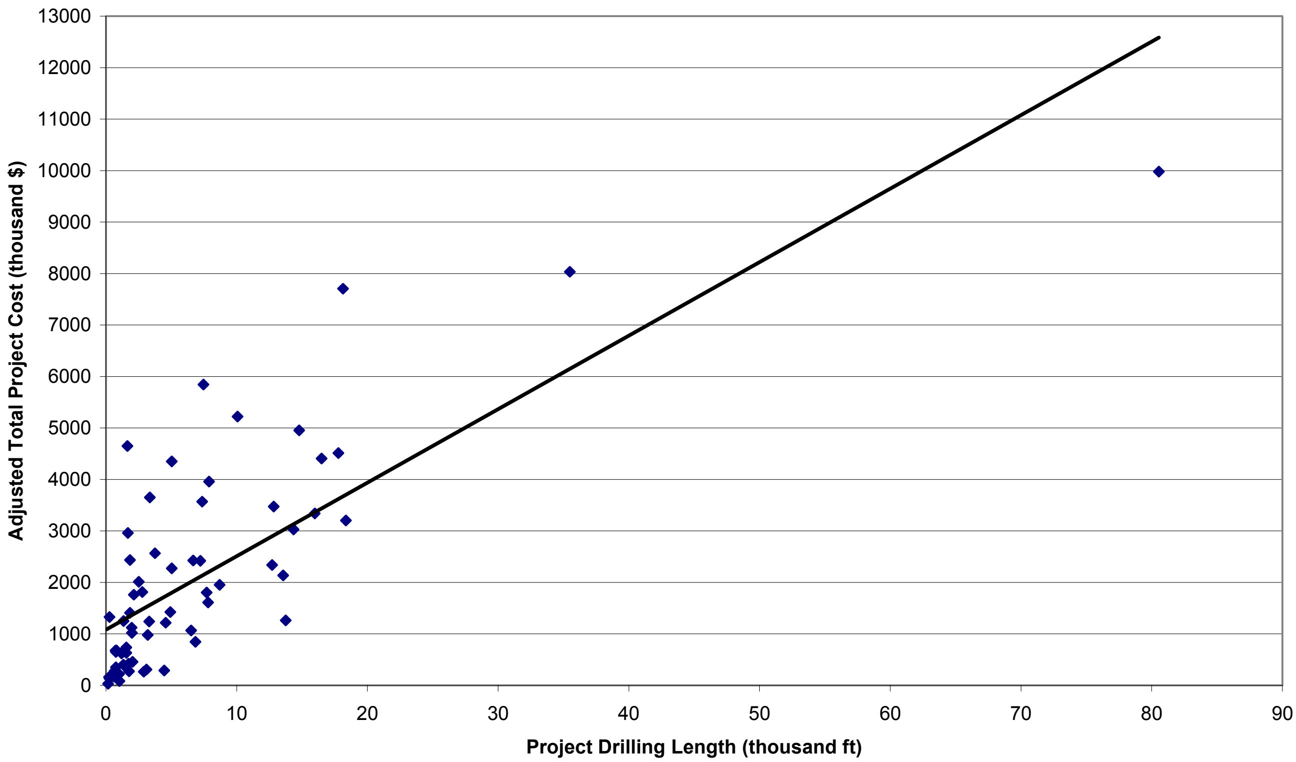

Figure 3. Drilling Length vs. Adjusted Cost

A similar graph based on the length of the pre-stressing steel is presented by Bruce and Wolfhope (2007b): it only includes data for multi-strand tendon anchors, excluding wire and bar anchors, to reduce the variation in the data. Since the available historical information on projects ranges from a simple reference to project costs in a published journal to detailed bid sheets and final payment estimates identifying installed quantities, there is a large degree of variation in the data as to what is included (or not included) in the costs. Table 2 provides statistics on anchor costs developed from the case study database.

Table 2. Summary of Anchoring Construction Costs

Statistic	Project Cost / Foot of Tendon[1]	Project Cost / Foot of Strand[2]
# Projects	100	92
Average	$450	$22
Minimum	$65	$1.25
Maximum	$1760	$83
Std Deviation	$340	$19

[1] Project cost expressed as dollars per foot of total tendon length
[2] Project cost expressed as dollars per foot of total strand length

The analysis of cost data from these 100 projects confirmed the difficultly of using general statistics such as cost per foot of drilled hole to estimate the project cost. Preparing cost estimates for dam anchoring projects is complicated by the many project specific aspects including geologic conditions, site access, site logistics, project location, schedule limitations, and design requirements. It is critical to evaluate the project specific aspects and constructability issues in developing project budgets.

CONCLUSIONS

The conduct of the research program into the use of prestressed anchors for dams has clearly illustrated the evolution of practice based on the implementation of "lessons learned" in key areas. In certain areas, the pace of the evolution has been very slow: we basically use the same design methods as our predecessors of 40 years ago. In other areas, especially corrosion protection, there have been important and rapid advances to address the fundamental concern expressed by practitioners regarding the long term reliability of prestressed anchor systems. More sophisticated testing and monitoring programs also provide confidence in future performance. The study has also illustrated progression in the contractual and administrative arrangements. Early projects were promoted and managed by post-tensioning specialists who subcontracted the "dirty work" of drilling and grouting to geotechnical contractors. Today, every major project is bid and managed by a specialty contractor (or in-house drilling and grouting forces) and the tendon supply is subcontracted, with most contractors doing their own stressing as well. This change simply reflects the reality of dam anchoring: it is a sophisticated specialty geotechnical process, not simply another application for post-tensioning materials and skills.

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